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This document constitutes a final report for our research in electromagnetic scattering during the years 2001--2003. The technical research accomplishments during each year divide conveniently into the areas of basic electromagnetic theory, scattering-matrix analysis of antenna arrays, and surface integral equations. Significant contributions were also made in the area of incremental length diffraction coefficients and toward the development of the Air Force cylindrical near-field scanning facility for measuring bistatic RCS. As principal investigator, Arthur D. Yaghjian carried out the major portion of the research, and coordinated his efforts with those of R.A. Shore, E.E. Altshuler, S.R. Best, U.H.W. Lammers, and R.A. Marr of the Air Force Research Laboratory, John Moore of SAIC, T.B. Hansen of Witten Technologies, T.H. O'Donnell of ARCON, and A.J. Devaney of A.J. Devaney Associates.

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Research in Electromagnetic Scattering

Final report for Contract # F49620-01-C-0018 submitted to the
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Abstract

This document constitutes a final report for our research in electromagnetic scattering during the years 2001–2003. The technical research accomplishments during each year divide conveniently into the areas of basic electromagnetic theory, scattering-matrix analysis of antenna arrays, and surface integral equations. Significant contributions were also made in the area of incremental length diffraction coefficients and toward the development of the Air Force cylindrical near-field scanning facility for measuring bistatic RCS. As principal investigator, Arthur D. Yaghjian carried out the major portion of the research, and coordinated his efforts with those of R.A. Shore, E.E. Altshuler, S.R. Best, U.H.W. Lammers, and R.A. Marr of the Air Force Research Laboratory, John Moore of SAIC, T.B. Hansen of Witten Technologies, T.H. O'Donnell of ARCON, and A.J. Devaney of A.J. Devaney Associates.

1 Technical Summary of Accomplishments

Our research accomplishments in electromagnetic scattering during each of the years 2001, 2002, and 2003 divide conveniently into three main areas:

- Basic Electromagnetic Theory
- Scattering-Matrix Analysis of Antenna Arrays
- Surface Integral Equations.

In addition, we continued the development and implementation of incremental length diffraction coefficients (ILDC's) in conjunction with SAIC and appreciably fostered the development of the cylindrical near-field scanning facility for measuring bistatic RCS at Hanscom AFB. This final report documents the progress made in these areas of electromagnetic research on a year by year basis.

1.1 Research in the Year 2001

This first year of the third millennium initiated the first year of the three-year contract. As proposed in that contract, Shore and Yaghjian continued the implementation and documentation of their ILDC's for improving upon the accuracy of physical optics fields with the publication of their shadow-boundary ILDC work and the surface-current equivalence theorem on which much of their ILDC formulation is based. As part of their ILDC work in FY-01, they demonstrated the distinct advantage of the exact ILDC's based on the equivalence theorem over the approximate ILDC's proposed by other authors. In particular, for scattering of a plane wave grazing upon a circular disc, the exact ILDC's predicted a reasonably accurate bistatic RCS that was 40 dB more accurate than the highly inaccurate bistatic RCS predicted by the approximate ILDC's. Invited reviews of their ILDC work were presented by Shore and Yaghjian, respectively, at the 2001 PIER Symposium held in Osaka, Japan and at the 2001 International Conference on Electromagnetics in Advanced Applications held in Torino, Italy. They continued helping SAIC incorporate shadow-boundary ILDC's into the Xpatch high-frequency computer code.

Dr. Yaghjian continued to consult in FY-01 with a number of Hanscom engineers and scientists, principally with Dr. Robert Shore (as mentioned above), with Dr. Edward Altshuler in designing small resonant wire antennas and small superdirective arrays (see FY-01 Annual Task Report submitted by Altshuler), and with Richard Marr and Dr. Uve Lammers on cylindrical near-field scanning of antennas and scatterers.

Basic Electromagnetic Theory

In the area of basic electromagnetic theory, Yaghjian was able to prove a three-dimensional (3-D) surface-current equivalence theorem analogous to the two-dimensional theorem used for finding ILDC's. This proof was done in part as a response to the number of inquiries he received from researchers in the USA and Europe who could see application of such a 3-D theorem in their own work. The 3-D theorem was presented at the 2001 Triennial International Symposium on Electromagnetic Theory in Victoria, BC, Canada, and was invited as one of a dozen papers for publication in a special issue of Radio Science devoted to the Symposium.

Scattering-Matrix Analysis of Antenna Arrays

In the year 2000, Yaghjian initiated a new area of research based on the source scattering-matrix analysis of arrays of radiators and scatterers. In FY-01, he was able to use the scattering-matrix analysis to explain at a fundamental level the reason why passbands and stopbands can be created in linear arrays with electrically small resonant elements. An invited talk on this subject was given by Yaghjian at a workshop on "Wave Dispersion in Complex Environments" held at the University of Siena, Italy, and an initial paper on the subject was accepted for publication in the IEEE AP-S Transactions.

Surface Integral Equations

In the area of surface integral equations, Shore and Yaghjian completed their work with the dual-surface electric-field integral equation (DSEFIE) applied to bodies of revolution, and a paper on this subject was presented at the 2001 PIER Symposium in Osaka, Japan. Also, in the area of surface integral equations, Yaghjian recast the conventional EFIE into a form whose kernel has no greater singularity than the $1/R$ singularity of the free-space Green's function. This allowed a simple method of moments solution using pulse basis functions and point matching. However, the method could only be applied effectively to smooth bodies. Still, the new integral equation, solvable by point matching with pulse basis functions, should prove useful in several applications. Thus, Shore and Yaghjian prepared the work for archival publication.

1.2 Research in the Year 2002

The second year of our contract was characterized by a number of promising new ideas and by the recognition of our past work through the Schelkunoff Prize Paper Award and several invited papers. In addition to our 2001 ILDC paper receiving the IEEE AP-S Schelkunoff Award, our recent work comparing our "source-based" ILDC's with approximate "diffraction-cone" ILDC's was invited to a special session at PIERS 2002 on "Recent Advances in Scattering and Diffraction," and was subsequently submitted for publication in the IEEE AP-S Transactions. Shore and Yaghjian began to consult with John Moore of SAIC on incorporating shadow-boundary ILDC's into the Xpatch high-frequency computer code.

Yaghjian has also been consulting with Richard Marr and Uve Lammers on their project for measuring bistatic RCS using cylindrical near-field measurements. In FY-2002 he discovered an extremely simple exact method for extracting the scattered fields from the total fields with a single displacement of the target, thereby endowing the MTI (moving target indicator) method for near-field measurements with the same accuracy and convenience it has exhibited for far-field measurements. Although background subtraction is the preferred method to extract the scattered near fields from the total measured near fields if the scanner tolerances are within a small fraction of a wavelength, this new MTI method becomes a viable alternative when the frequency is high enough that the scanner fails to measure the phase with sufficient accuracy.

Basic Electromagnetic Theory

In the area of basic electromagnetic theory, Yaghjian found a more robust way to eliminate the pre-acceleration from the classical equations of motion of charged particles that also eliminates pre-deceleration. He plans to include this important revision in the second edition of his Springer-Verlag monograph scheduled for publication in 2005.

An investigation into the origin of precursors revealed a definitive method for determining the far-field behavior of the Brillouin precursor for an arbitrarily shaped initial pulse in a Lorentz dispersive medium.

Yaghjian also refined the proof of his 3-D surface current equivalence theorem, applied it to obtain a linear differential operator representation for antennas, and submitted the manuscript as an invited paper to the special issue of Radio Science.

An invited paper on the primary forms of Maxwell's equations was presented in an electromagnetic theory session of PIERS 2002. In this paper, he proved that the classical constitutive relations for polarized media requires that Maxwell's equations in free space be expressed in terms of $(\mathbf{E}, \mathbf{B})$ or $(\mathbf{D}, \mathbf{H})$ depending upon whether electric or magnetic charge-current is the primary source of the fields.

Scattering-Matrix Analysis of Antenna Arrays

In the area of linear arrays, Shore and Yaghjian formulated a spherical-wave source scattering-matrix description of electromagnetic radiators (antennas and scatterers rather than acoustic radiators, which were treated in their previous scattering-matrix work). When the electromagnetic formulation is applied to linear arrays of dipoles (Yagi-Uda antennas), simple expressions are found for the propagation constants of the traveling waves. These predicted values of the propagation constants agreed well with measured values for Yagi-Uda antennas over a considerable range of dipole heights and separation distances. This general, yet practical method for analyzing arrays of electrically small radiators holds promise for predicting the behavior of and designing composite materials constructed from one-, two-, and three-dimensional arrays of small resonant antennas and scatterers.

Yaghjian also continued to support the experimental and computational work at Hanscom on electrically small superdirective arrays of resonant antennas with analyses that explained the computed far-field patterns, that compared various methods used to compute Q, and that determined a reliable method to compute ohmic losses in wire antennas. In addition, he came up with the idea for the dual directional coupler microwave measurement system (and a simple way to calibrate it) that enabled the recent experimental verification of superdirectivity with two coupled resonant monopoles. This work was presented as an invited paper to the XXVIIth URSI General Assembly.

Surface Integral Equations

Our work in both the areas of surface integral equations and ILDC's has been nearing completion. We were pleased to discover that a minor change in our low singularity EFIE computer program allowed the simple pulse-basis point-matching numerical solution to converge as well as the original EFIE with higher order basis and testing functions. On the other hand, the low singularity EFIE has to be modified when applied to scatterers with edges and this complicates the numerical solution to this EFIE which was derived specifically to allow an uncomplicated numerical solution. The work was invited to a special session at PIERS 2002 on "Novel Mathematical Methods in Electromagnetics," and Shore, who delivered the talk to a full house, received many questions at the end of his talk that continued for an hour after the session.

1.3 Research in the Year 2003

As we approached the end of our three-year contract in "Research in Electromagnetic Scattering" we were pleased to report that all but one of the tasks that were proposed, and appreciably more, have been accomplished. During the three years, we completed the documentation of our ILDC work with the publication of four archival journal papers, one of which won the Schelkunoff Prize Paper Award, and we continue to assist in the implementation of ILDC's into production high-frequency-scattering and reflector-antenna computer codes. Yaghjian also continues to consult with Marr, Lammers, and Hansen on measuring bistatic RCS using cylindrical near-field measurements. His experience with the theory of near-field scanning as well as with methods to reduce the errors involved with target displacement and background subtraction have helped advance the progress of this project. Work on "time-domain fields and forces in polarized media" was not completed during the past three-year contract because of prevailing tasks that arose on superdirective arrays, on near-field cylindrical RCS measurements, on the far-fields of Brillouin precursors, and on the bandwidth and Q of antennas. Completion of the "polarized media" work is proposed as part of the research during the next three years.

Basic Electromagnetic Theory

In the area of basic electromagnetic theory, a general perturbation solution to the Lorentz-Dirac equation of motion for accelerated charges was derived and applied to determine more accurate trajectories and radiation forces of charged particles. As part of a recent research proposal submitted to AFOSR, we would include this perturbation solution, along with other additions and revisions detailed in the proposal, into a second edition of Yaghjian's 1992 Springer-Verlag book on the classical equations of motion of charged particles.

In response to an absence in the published literature of a definitive expression for the far-field behavior of the Brillouin precursor of an arbitrarily shaped initial pulse, Yaghjian derived a rigorous integral expression for the far field of the Brillouin precursor and evaluated this expression for a number of pulse shapes. When time permits, he plans to generalize and numerically verify this evaluation for an arbitrary pulse. During the last year, his attention shifted temporarily from this interesting work with Brillouin precursors to a pressing project at AFRL/SNHA requiring the accurate determination of bandwidth and Q of realistically tuned antennas. This work has led to the derivation of new, disarmingly simple, yet highly accurate, formulas for the bandwidth and Q of antennas tuned to any frequency. Best and Yaghjian have been working together to complete this research and its documentation. Their preliminary results were presented by Yaghjian in a paper invited to a special metamaterials session of the June 2003 IEEE AP-S Symposium.

Scattering-Matrix Analysis of Antenna Arrays

In regard to the "spherical-wave source scattering-matrix analysis of periodic arrays," we completed the translation of the theory from the scalar fields of acoustic radiators to the

vector fields of electromagnetic antennas and scatterers, and applied this electromagnetic formulation to determine explicit expressions for the propagation constants of the traveling waves on Yagi-Uda arrays and on arrays of small magnetodielectric spheres, which exhibit "backward traveling waves" and thus are candidates for the development of "double negative" composites.

Yaghjian continued his support of the experimental and computational work at Hanscom on electrically small superdirective arrays of resonant antennas by estimating ground-plane losses and co-authoring the theoretical portion of a recently prepared paper on superdirective monopole arrays.

Surface Integral Equations

In the area of surface integral equations, Shore and Yaghjian completed the documentation of the dual-surface electric-field and magnetic-field integral equations and the low-singularity EFIE applied to general bodies of revolution (BORs). Having both a DSEFIE and a DSMFIE BOR code has proven invaluable for obtaining reliable solutions for bistatic scattering from canonical targets of interest to AFRL scientists and engineers.

2 Principal Publications

2.1 Published Articles

1. R.A. Shore and A.D. Yaghjian, "Shadow boundary incremental length diffraction coefficients applied to scattering from 3-D bodies," *IEEE Transactions on Antennas and Propagation*, vol. 49, pp. 200-210, February 2001.

2. A.D. Yaghjian, "Incremental length diffraction coefficients for arbitrary cylindrical scatterers," *IEEE Transactions on Antennas and Propagation*, vol.49, pp. 1025-1032, July 2001.

3. A.D. Yaghjian, "Scattering-matrix analysis of linear periodic arrays," *IEEE Transactions on Antennas and Propagation*, vol. 50, pp. 1050–1064, August 2002.

4. R.A. Shore and A.D. Yaghjian, "Dual-surface integral equations in electromagnetic scattering," Proceedings of the XXVIIth URSI General Assembly, Maastricht, Netherlands, pp. B2.0.5.1–B2.0.5.4, August 2002 (Invited).

5. E.E. Altshuler, T.H. O'Donnell, and A.D. Yaghjian, "Superdirective arrays using very small antennas," Proceedings of the XXVIIth URSI General Assembly, Maastricht, Netherlands, pp. B8.P.6.1–B8.P.6.4, August 2002 (Invited).

6. A.D. Yaghjian, "Three-dimensional planar surface-current equivalence theorem with application to receiving antennas as linear differential operators," *Radio Science*, vol. 38, pp. 4-1 – 4-10, March–April 2003 (Invited).

7. A.D. Yaghjian and S.R. Best, "Impedance, bandwidth, and Q of antennas," *Proc. IEEE AP-S Symposium*, vol. 1, pp. 501–504, June 2003 (Invited).

8. S.R. Best and A.D. Yaghjian, "Impedance, bandwidth and Q of the general one-port antenna, *Proc. Antenna Applications Symposium*, pp. 373–402, September 2003.

9. A.D. Yaghjian, "A comparison of high-frequency scattering determined from PO fields enhanced with alternative ILDC's," *IEEE Trans. Antennas and Propagat.*, vol. 52, January 2004.

2.2 Reports

1. R.A. Shore and A.D. Yaghjian, *Dual Surface Electric Field Integral Equation*, AFRL In-House Report, October 2001.

2. A.D. Yaghjian, *Research on Electrically Small Super-Directive Arrays*, Final Report for project FY01-DYTN-DCN1031, AFRL, Hanscom AFB, December 2001.

3. R.A. Shore and A.D. Yaghjian, *Scattering-Matrix Analysis of Linear Periodic Arrays of Short Electric Dipoles*, AFRL Technical Report, Hanscom AFB, submitted September 2003.

2.3 Presentations

1. A.D. Yaghjian, "Scattering-matrix analysis of linear periodic arrays," *Digest of National Radio Science Meeting (Boulder, CO)*, p. 127, January 2001.

2. R.A. Shore and A.D. Yaghjian , "Shadow boundary incremental length diffraction coefficients to bistatic scattering from 3-D bodies," *Proceedings of PIERS (Osaka, Japan)*, p. 118, July 2001 (Invited).

3. R.A. Shore and A.D. Yaghjian , "Dual surface electric-field integral equation," *Proceedings of PIERS (Osaka, Japan)*, p. 392, July 2001.

4. A.D. Yaghjian, "Scattering-matrix analysis of linear periodic arrays," *Workshop on Wave Dispersion in Complex Environments (Siena, Italy)*, September 2001 (Invited).

5. A.D. Yaghjian, "Scattering-matrix analysis of linear periodic arrays with resonant elements," *Digest of National Radio Science Meeting (San Antonio, TX)*, p. 112, June 2002 (Invited).

6. A.D. Yaghjian, "Primary forms of Maxwell's equations in free space," *Proceedings of PIERS (Boston, MA)*, p. 94, July 2002 (Invited).

7. R.A. Shore and A.D. Yaghjian , "Solving the electric field integral equation using the method of moments with pulse-basis functions and point matching," *Proceedings of PIERS (Boston, MA)*, p. 578, July 2002 (Invited).

8. A.D. Yaghjian and R.A. Shore, "Comparison of high-frequency scattering results using exact and approximate incremental length diffraction coefficients," *Proceedings of PIERS (Boston, MA)*, p. 846, July 2002 (Invited).

9. J. Moore, L. Lawson, D. Kapp, and A.D. Yaghjian, "Creeping waves and truncated wedge ILDC's in Xpatch," *EMCC Annual Meeting (NASA-Langley Research Center, Hampton, VA)*, May 2003.

10. A.D. Yaghjian, "Impedance, bandwidth, and Q of antennas," *Electroscience Laboratory, OSU*, June 2003 (Invited).

11. A.D. Yaghjian, "Impedance, bandwidth, and Q of antennas," *National Institute of Science and Technology, Boulder, CO*, July 2003 (Invited).

12. R.A. Shore and A.D. Yaghjian, "Improving physical optics with incremental length diffraction coefficients," *Proceedings of PIERS (Honolulu, HI)*, p. 191, October 2003 (Invited).

13. A.D. Yaghjian and R.A. Shore, "Applications of spherical-wave source scattering-matrix analysis of lossless, reciprocal antennas," *Proceedings of PIERS (Honolulu, HI)*, p. 237, October 2003 (Invited).

In closing, the research of the principal investigator and his collaborators continues to be recognized through awards, numerous citations, invitations to present and submit papers, and in 2003 through an invitation for Yaghjian to serve as an "IEEE Distinguished Lecturer" for the Antennas and Propagation Society during the years 2003–2005.